SURFACE CHARACTERIZATION AND MODELING FOR COATINGS

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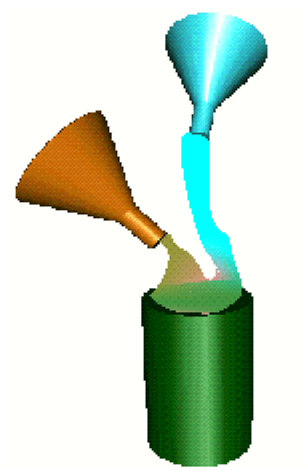
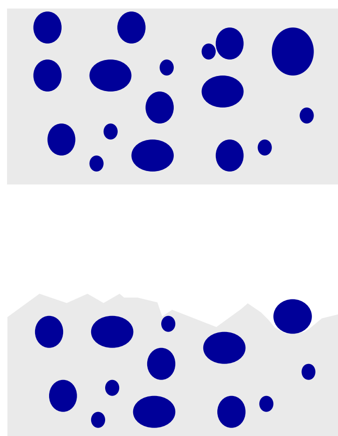
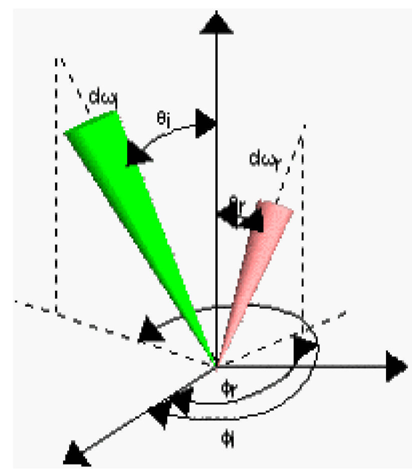
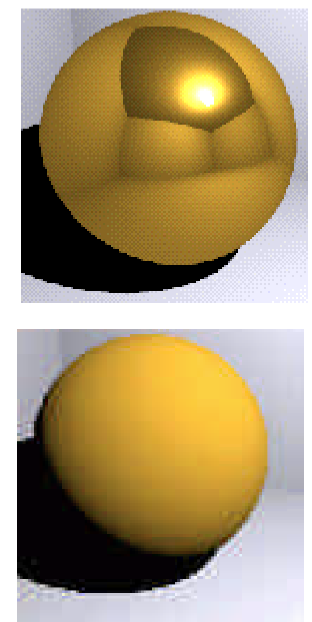
Color and appearance program

Formulation → **Micro-Structure** → **Reflectance** → **Appearance Parameters**









Topics

- Sample preparation
- Surface topography maps
- Computation of the BRDF of rough surfaces
    - Kirchhoff approximation
    - Ray approximation
- Comparison with measured reflectance curves

Sample Preparation

- Epoxy samples on black glass substrates were prepared at NIST on a relatively rough steel surfaces that had been systematically modified using a polymeric solution

- The samples provided surfaces of controlled isotropic roughness. The final roughness depended on the mass fraction of the polymeric solution

- Another type of sample was prepared as a black-glass replica. It was very smooth and approximated well an optically flat surface

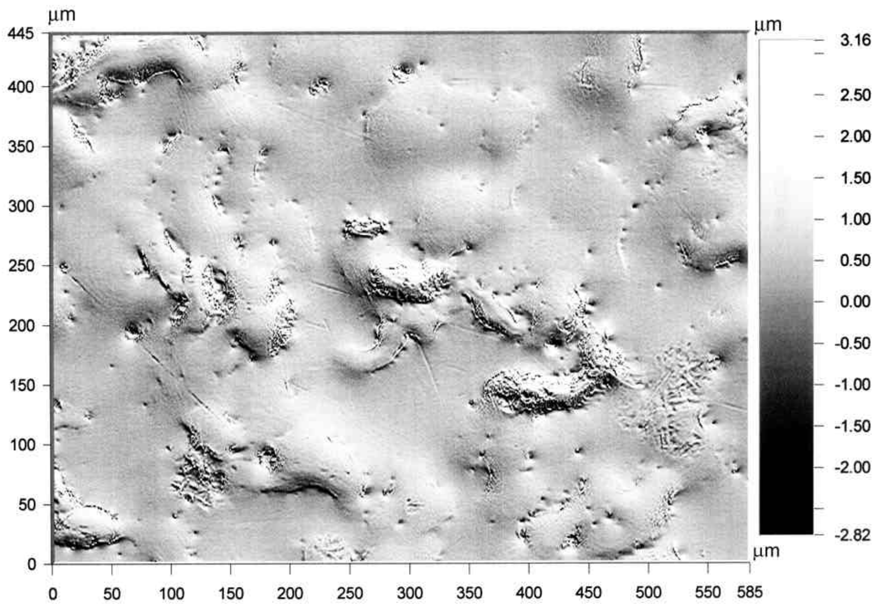
Surface Topography Map

Measure $z = \zeta(x,y)$ over a region S in the xy-plane.

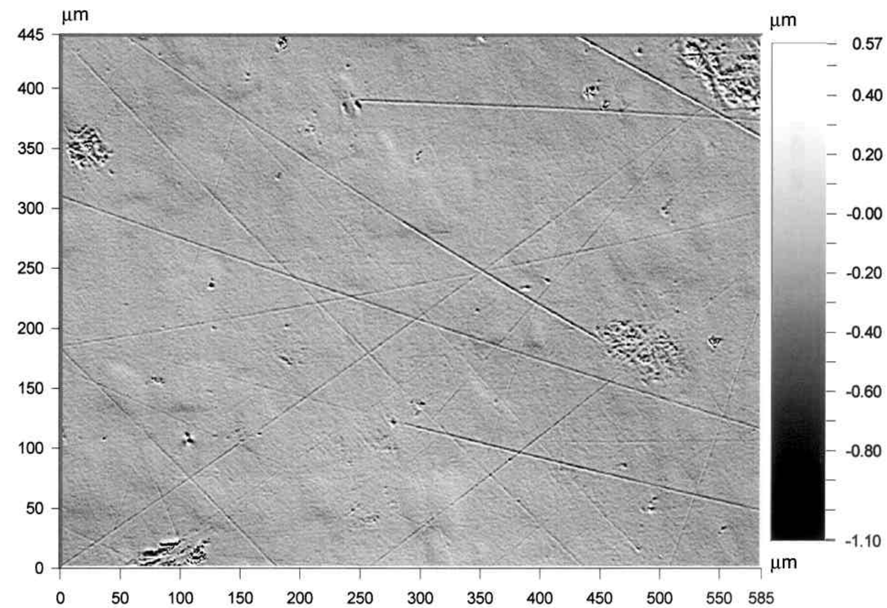
Methods:

- Stylus profilometry (sufficient for statistically isotropic surface if a single trace is taken)
- White-light interferometric microscopy (point spacing of the order of the wavelength of light)
- Atomic force microscopy (closely spaced points, small area coverage)

Images



Rough sample, σ = 805 nm



Smooth sample, σ = 201 nm

Measured with a WYKO interferometric microscope

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Particles Below the Surface

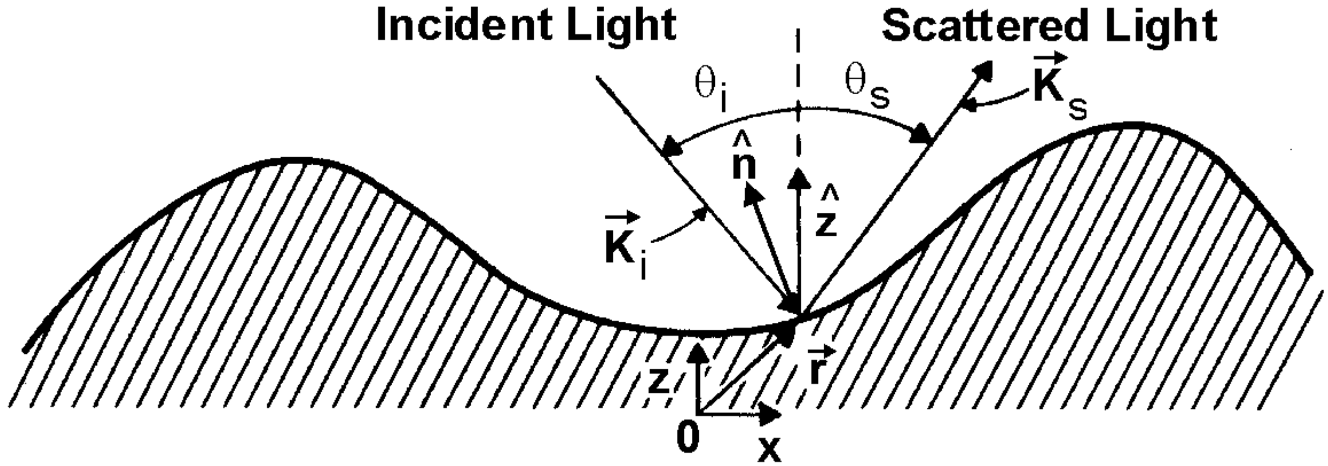
For future modeling:

- TiO_2 and other pigments (particles of size comparable to λ)
- Metallic flakes (disks about 30 μm in diameter)
    - Shape
    - Density
    - Orientation
- Pearlescent paints

Reflectivity and BRDF Computation

- Phase integral in the Kirchhoff approximation (Beckmann)
- Ray approximation for locally flat surfaces
- Integral equations for exact solution of Maxwell's equations

Kirchhoff Approximation Diagram



Light scattered by a rough surface from an incident plane wave

Kirchhoff Approximation

- Scalar wave equation for the amplitude ψ
- The field at the surface is equal to the incident field plus the field reflected by the tangential plane in the illuminated region
- Field vanishes outside the illuminated region
- Leads to discontinuities in the field at the edge of the illuminated region
- Multiply by windowing functions W(x,y)

Equations in Kirchhoff Approximation

$$\psi(\theta_i, \varphi_i; \theta, \varphi) = F_3(\theta_i, \varphi_i; \theta, \varphi) \int_\Sigma W(x, y) \exp[i\vec{v}(\theta_i, \varphi_i; \theta, \varphi) \cdot \vec{x}(x, y)] dxdy\ ,$$

where

$$F_3(\theta_i, \varphi_i; \theta, \varphi) = \frac{1 + \cos\theta_i \cos\theta + \sin\theta_i \sin\theta \cos(\varphi - \varphi_i)}{\cos\theta_i (\cos\theta_i + \cos\theta)}\ ,$$

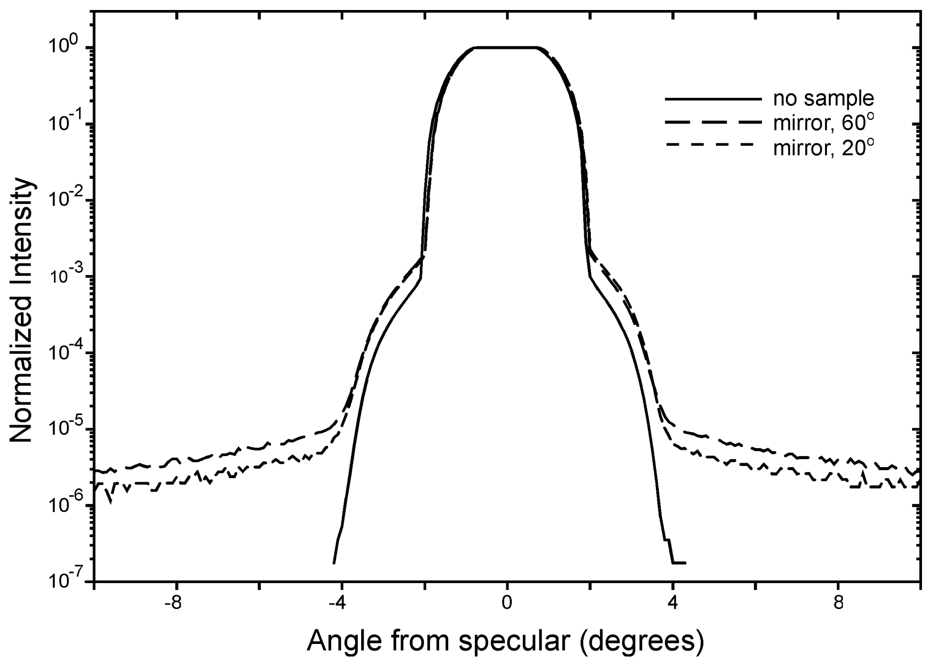
$$\vec{v} \cdot \vec{x} = -k[(\sin\theta_i \cos\varphi_i + \sin\theta \cos\varphi)x + (\sin\theta_i \sin s\varphi_i + \sin\theta \sin\varphi)y$$

$$+ (\cos\theta_i + \cos\theta)\zeta(x, y)].$$

To computer the integral: about ten points/wavelength (spline interpolation)

Convolution with Instrument Response

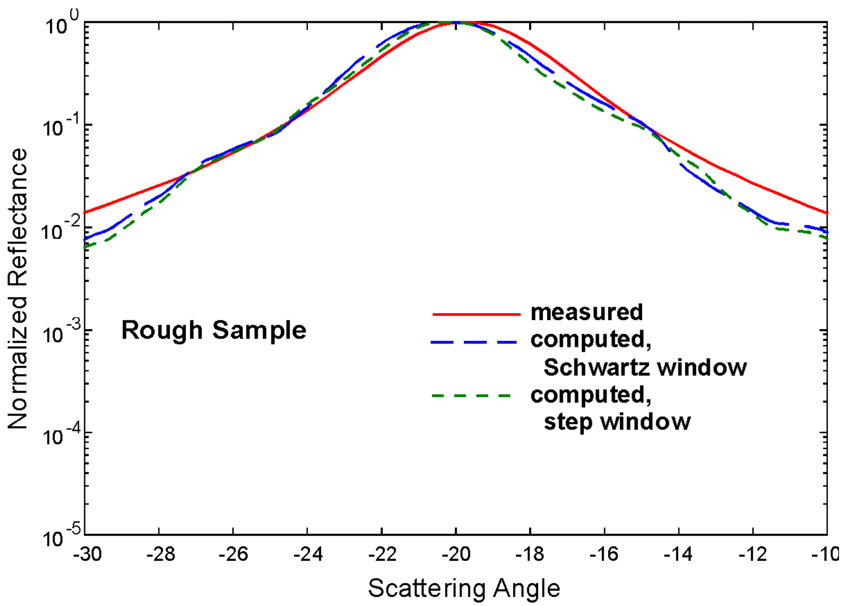
- Instrument signature can be measured with:
    - No target or
    - Mirror at the angle of incidence
- Instrument signature represents:
    - Apertures in the detector
    - Stray light
    - Mirror residual roughness
- Convolution integral

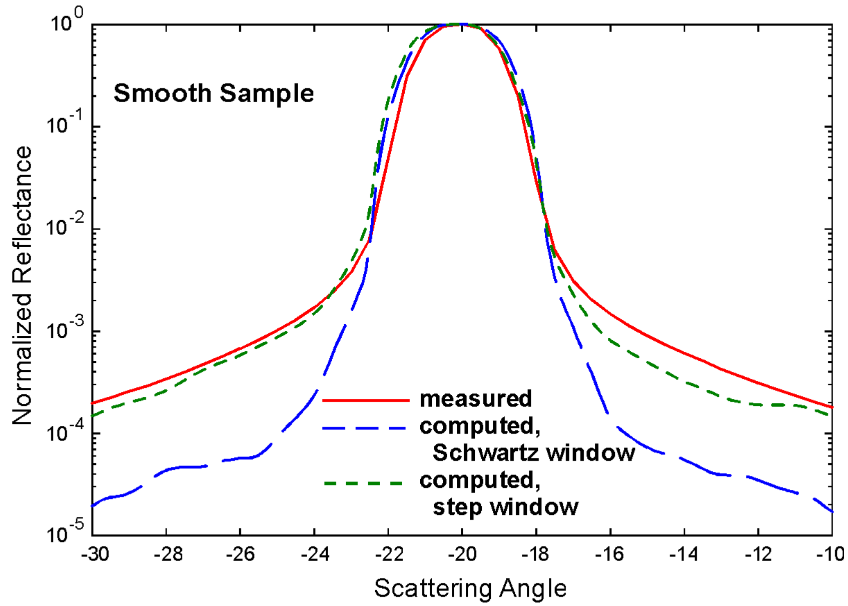


$$\bar{I}(\theta) = \int_{\theta_1}^{\theta_2} I(\theta') I_r(\theta - \theta') d\theta', \qquad -\pi/2 < 0 < \pi/2$$

$$\theta_1 = \max(-\pi/2, -\pi/2 - \theta), \qquad \theta_2 = \min(\pi/2, \pi/2 + \theta)$$

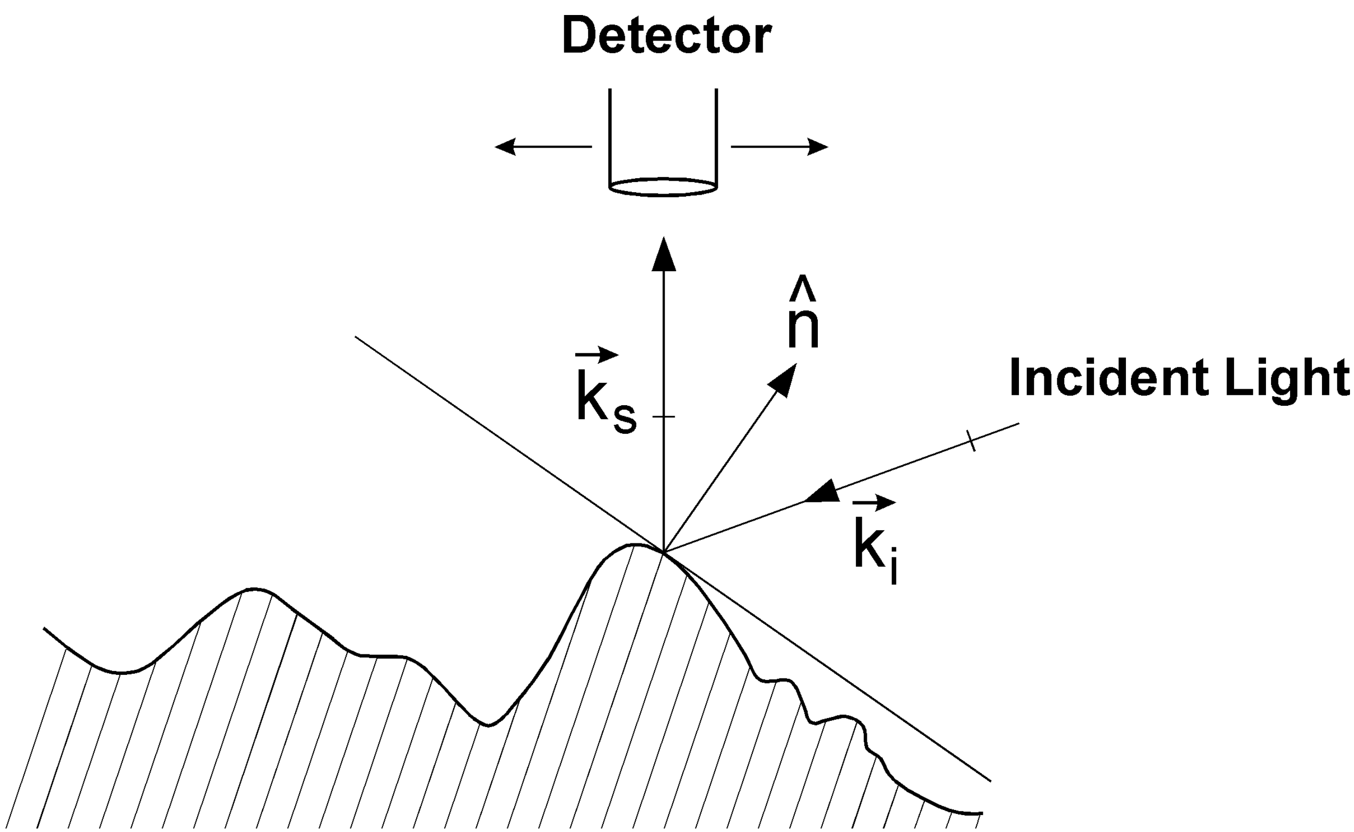
Comparison with Measured Reflectance





- Agreement near the specular direction is good, and the shapes of the curves clearly depend on the roughness.
- Further away, for the smooth sample, there is a small discrepancy that may be due to the method of calculation and/or to the areas used in the map and in the scattering measurement.

Ray Approximation Diagram



Specular reflection of a ray of light incident on a rough surface

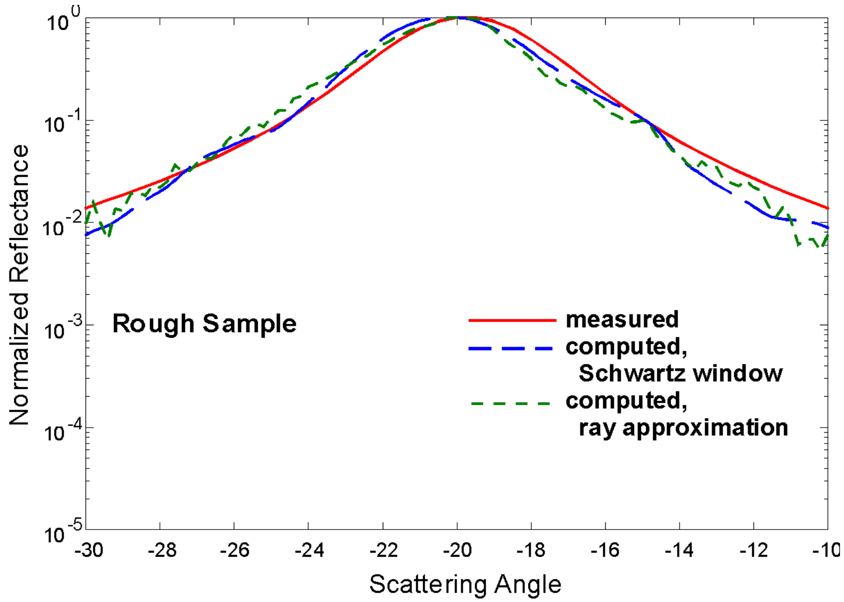
Ray Approximation

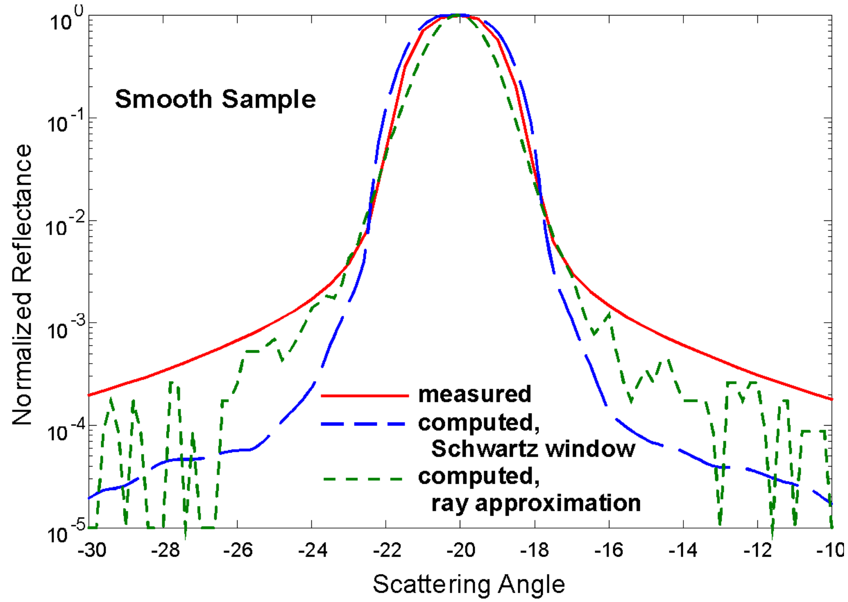
Given a topographic map of a region on a surface,
for each interior point:

- Determine an approximate tangent plane
    - by a least-squares fit
    - from a two-dimensional spline fit
- Find the reflected ray
- Check whether a detector catches the reflected ray
- Total the number of rays caught by each detector and normalize

Fast, giving a reasonably good approximation

Comparison of Ray and Kirchhoff Approximations





- The ray approximation is good for these kinds of surfaces.
- For the smooth sample, the ray seems to agree better with the Kirchhoff approximation than with the measured reflectance.

Conclusions

- Reflectances computed using the measured surface maps reproduce measured reflectances near the specular direction for the samples in this study.

- Different measurements cover different areas, which may influence computed results.

- The identity of the sample can be determined from the reflectance. (The roughness correlates with the percentage of epoxy used in the preparation.)

- The ray approximation reproduces quite well the much longer calculation using the Kirchhoff approximation. Thus this approximation can be used for computations involving the many directions of incidence and detector locations needed for rendering.